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INITIAL STUDY OF THE EFFECT OF CRYOSURFACE GEOMETRY ON CRYOPUMPING

By

J. A. Collins, Jr., J. D. Haygood, and E. S. J. Wang
Aero-Space Research, Office of D/E
ARO, Inc.

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ABSTRACT

An experimental study of cryogenic pumping using several cryosurfaces in the pressure ranges of 10^{-4} and 10^{-3} mm Hg is presented. At these pressures, where the mean free path of the condensable gas is on the order of the cryosurface dimensions, it is shown that the pumping rate is no longer a constant as it is in free-molecular flow, but increases through what is termed the transition range and presumably approaches a higher constant value in the continum flow regime. Flow in the gas kinetic, gas dynamic, and transition regimes is discussed.

Experimental results are presented showing the effects on cryopumping of the addition of fins or ribs to a cryosurface, and the effect of pumping with parallel cryosurfaces at different separations.

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NOMENCLATURE

A	Cryosurface area, cm^2
d	Molecular diameter, cm
k	Boltzman constant
M	Molecular weight, g/g-mole
p	Pressure, mm Hg
p_o	Pressure of inflowing gas, mm Hg
P.R.	Pumping rate, liters/sec
Δp	Partial pressure of condensable gas, mm Hg
R	Gas constant
T	Temperature, °K
dV_o/dt	Inflow rate of condensable gas at pressure p_o, liters/sec
γ	Specific heat ratio
λ	Mean free path, cm

SUBSCRIPTS

$( )_{fm}$	Free-molecular conditions (gas kinetic)
$( )_c$	Continum flow conditions (gas dynamic)
$( )_t$	Transition range conditions

1.0 INTRODUCTION

Because the cryogenic vacuum pumping technique has been found to be practical and economical for application to large vacuum chambers (Refs. 1, 2, and 3), a study of the parameters significant to cryopumping is important. One of the most important limitations of cryopumping which can be stated a priori is that the pressure in the system must always be greater than the vapor pressure of the various condensate gases at the temperature of the cryosurface; for example, at liquid helium temperature the only noncondensable gas left in the chamber will be helium, itself. Interrelated with the temperature effect is the effect produced on cryopumping by the pressure of the system. An earlier investigation (Ref. 4) was made of the pumping rate for several gases as a function of chamber pressure. That investigation showed that in the free-molecular flow region experiment agrees with kinetic theory in that volumetric pumping speed is constant. In addition, those results indicated that the pumping speed was reduced in the pressure range where the chamber pressure approaches the vapor pressure of the condensate. The question naturally arises as to the effect on cryopumping of increasing the chamber pressure beyond that of the free-molecular flow region. No information pertaining to this effect has been published.

Fluid mechanics, in general, can be separated into the three regions: continuum, transition, and free-molecular flow. In the well-known continuum region, the intermolecular collisions are the governing physical phenomena, whereas in the free-molecular flow region the molecule-surface interactions are the governing phenomena. The transition region, however, is unique in that both intermolecular and molecule-surface collisions must be considered. To determine the flow region for a particular fluid dynamics problem, a dimensionless parameter known as the Knudsen number, K_n, is usually used. The Knudsen number is the ratio of the mean free path to a characteristic body dimension, and therefore expresses the degree of interaction between molecules. Based on the Knudsen number, the three flow regimes are arbitrarily separated into the following ranges (Ref. 5): for K_n less than 0.01, the flow is in the continuum region; for K_n between 0.01 and 10, the flow is said to be in the transition region; and for K_n greater than 10, free-molecular flow conditions prevail.

The capabilities of modern low-density wind tunnels are being expanded beyond the well-developed continuum flow regime into the region of transition flow. Removal of the mass flow and reduction of the nozzle

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boundary layer in the low-density tunnels by cryopumping is being contemplated (Ref. 6). Thus, it is necessary to understand cryopumping, not only in the free-molecular flow region where most space simulation chambers will operate, but also in the transition and continuum flow regimes.

This report deals with the cryopumping rates mainly in the pressure ranges where the free-molecule and transition regimes are predominant. With the use of several cryosurfaces, the effects of the transition regime on cryopumping are examined, and an effect of cryosurface geometry on cryopumping in the free-molecule regime is noted and discussed.

2.0 APPARATUS

The experiments were performed in a vacuum chamber, 20 inches in diameter and 30 inches in length (Fig. 1). The details of the chamber are the same as those previously reported (Ref. 4), with the exception that the 4-inch pumpout line and high vacuum gate valve were replaced by 6-inch components.

A set of cylindrical parallel plate cryosurfaces, 4-inches in diameter and one inch thick, and several variations of finned cryosurfaces were employed in this series of experiments. Figure 2 shows the parallel plates, the 18-fin cylinder, and the 3-fin cylinder. For the 18-fin surface, the cylinder is one inch in diameter and 3.5 inches long with fins 0.5 inch in depth and 3.5 inches long. For the 3-fin surface, the cylinder is 0.75 inch in diameter and 3.5 inches long with two sets of fins that are one inch (shown in the figure) and 0.5 inch in depth. Each set of fins was mounted on the cylinder by brazing with silver solder. All of the cryosurfaces employed a vacuum-jacketed transfer line for the purpose of limiting condensation in the chamber to the cryosurface. However, this was not entirely successful, and there was a small but not negligible deposit on the vacuum jacket adjacent to the cryosurface, caused by conduction cooling of the vacuum jacket. In most cases, this excess area amounted to approximately five percent of the total cryosurface pumping area. Fortunately, for any given configuration, the deposit area was constant so that a correction for the additional cryopumping surface could be made. A flexible, vacuum-jacketed, liquid nitrogen feed line was used with the parallel plates to allow variation of the distance between the plates.

Carbon dioxide was used as the condensable gas in these experiments, and liquid nitrogen was used as the cryogenic fluid. Commercial CO_2 was too impure for the experiments and was purified before use by a vacuum recrystallization method (Ref. 4). The purified CO_2 was then passed through a pressure regulator and a calibrated flowmeter. The flow was controlled with a metering valve and could be stopped completely with a solenoid valve located in the line at the entrance to the chamber. On entering the vacuum chamber, the CO_2 was directed against the wall of the chamber for diffusion purposes.

The instrumentation used in these experiments included an Alphatron for measuring pressures above 10^{-3} torr and an ionization gage for measuring pressures below 10^{-3} torr. Both gages were calibrated for N_2 gas, and a conversion factor of 0.633 was used to obtain CO_2 pressure. Also, four copper-constantan thermocouples, calibrated to liquid nitrogen temperature, were used in the temperature study on the 3-fin cylinder. A multipoint recorder was used to measure the thermocouple output.

3.0 PROCEDURE

Each series of experiments on the finned cryosurfaces and the parallel plate cryosurfaces was performed in the same manner. When any particular cryosurface was installed in the vacuum chamber, pump-down operation began. With the cryosurface at room temperature, the pump-down operation was continued for several hours until the chamber pressure reached approximately 5×10^{-6} torr. At this time, the liquid nitrogen flow was introduced to the cryosurface. When a steady flow of liquid nitrogen was established through the cryosurface, the cryosurface had reached approximately the temperature of liquid nitrogen.

Before actual testing was started, the cryosurface was coated with a visible deposit of CO_2 to eliminate the bare surface effect (Ref. 4). Then, with the cryosurface visibly coated with CO_2 and at liquid nitrogen temperature, the chamber was pumped down to approximately 2×10^{-7} torr, the vacuum valve was closed to isolate the mechanical pumps from the chamber, and a constant CO_2 inleakage, or flow, to the chamber was established, continued for approximately 3 minutes and shut off. The pumping rate could be calculated from the pressure data which were continuously recorded through the flow period. Prior to each test, the chamber was pumped down to the pressure range mentioned above. The total chamber pressure of each test was controlled by varying the CO_2 inleakage flow rate. Only ten such tests were made at any

one time before the cryosurface was warmed to room temperature, and the test procedure started again. This was done to eliminate excessive build-up of CO_2 frost on the cryosurface which might have caused significant changes in surface area and temperature. The data sheet of a typical test for the 18-fin cylinder is presented in the following table:

Test No.	Flow Rate, cc/sec (NTP)	CO_2 Partial Pressure, mm Hg x 10^4	Chamber Pressure, mm Hg x 10^4
1	0.77	3.18	3.29
2	0.41	1.63	1.72
3	0.96	3.81	3.96
4	1.17	4.74	4.90
5	1.37	5.27	5.46
6	0.26	1.04	1.12
7	0.32	1.25	1.33
8	0.63	2.47	2.56
9	1.11	4.36	4.48
10	1.71	6.61	6.86

4.0 RESULTS AND DISCUSSION

The experimental results are presented in the form of pumping rates as a function of pressure. Based on the data similar to those listed in the above table, pumping rates for each cryosurface configuration can be calculated by the following equation:

$$P.R. = \frac{760}{\Delta p}\left(\frac{dV_o}{dt}\right)$$

where dV_O/dt is the flow rate in cc/sec (NTP) and Δp is the partial pressure of CO_2. Experimentally, the CO_2 partial pressure in the previous table is obtained in each run by observing the pressure drop in the pressure-time curve after the constant inleakage flow is stopped. This method of calculating pumping rate is discussed at length in Ref. 4.

For determining the mean free path of CO_2 in the interpretation of experimental data, the following equation, as recommended by Present (Ref. 7), is used:

$$\lambda = \frac{kT}{2p\pi d^2}$$

Figure 3 shows a plot of mean free path for carbon dioxide as a function of pressure at room temperature and at 77°K.

4.1 3-FIN CRYOSURFACES

As stated previously, two sets of 3-fin surfaces were employed. Including the base cylinder without fins, a total of three different cryosurfaces was used in this series of tests. The experimental results obtained from these cryosurfaces in terms of pumping rate versus chamber pressure are shown in Fig. 4. It should be noted that the pumping rate is given in liters per second and not in the usual liters/cm^2-sec units characteristic of cryogenic pumping. The unit of area was not included in the pumping rate calculation because in several cases, as will be seen later, the actual surface actively cryopumping was not known. Since, however, this is essentially a comparison study, the units of pumping rates are of secondary importance.

In further examining Fig. 4, it can be seen that in the lower pressure range, the pumping rate in all three cases is constant within experimental error. Considering this range of pressure to be in the free-molecular flow region, the experimental data agree with kinetic theory with a capture coefficient of approximately 0.55 based on the total cryosurface area. On going to higher pressures, a region is reached where the pumping rate is no longer constant, but begins to increase with increasing pressure. This is believed to be the start of the transition range in going from the free-molecular flow to the continuum region. Curves A and B, which are the data collected on the cylinder without fins and with 0.5-inch fins, respectively, cover the transition range and appear to reach a leveling-off value of pumping rate which is considered to be approaching that of the continuum flow regime. Curve C, which represents data from the cylinder with one-inch depth fins, could not be extended to a leveling-off region where constant pumping rate would be evident. The limitation in extending experimental data into the continuum region is attributed to thermal overloading of the cryosurface, as the temperature of the fins is obtained solely by conduction from the liquid-nitrogen-cooled cylinder. Thus, at the higher pressures, which means higher flow rates of CO_2, the outward portions of the fins were subject to a thermal overload which resulted in a severe reduction in pumping rate. This overloading was observed visually and experimentally. As the flow rate was increased, the CO_2 deposit on the outer regions of the fins began to flake off. Experimentally, thermocouples were placed on the 0.5-inch fins and a temperature gradient was measured across the fins. At a CO_2 flow rate of 65 cc/sec, for example, the gradient across the fins was over 55°K, i.e., the temperature of the outer edge of the fin was above 132°K.

4.2 18-FIN CYLINDER CRYOSURFACE

The data collected for the 18-fin cylinder cryosurface in the free-molecular flow region and in the beginning of the transition region are given in Fig. 5. Again thermal overloading of the fins prevented obtaining data in the continuum range of flow.

In the free-molecular flow region, the experimental pumping rate is approximately 1850 liters/sec. This pumping rate is higher than that which can be explained by kinetic theory using the surface area of the base cylinder and lower than that using total surface area of the fins and base cylinder. It is found that if the envelope area of the 18-fin cylinder, which is the projected area of a cylinder with radius equal to fin depth plus the radius of the actual cylinder, is used, and if the capture coefficient is chosen as unity, the calculated pumping rate based on kinetic theory agrees with the experimental value.

In order to understand this envelope-area concept, comprehension of the mechanism of molecular motion near the cryosurfaces is necessary. In the free-molecular flow region, the number of molecules at ambient temperature hitting a unit area of surface also at ambient temperature per unit time can be calculated by kinetic theory, and the rate of molecules hitting the surface will be equal to the rate of molecules which are rebounding from the surface. If the surface is cold, a non-equilibrium condition would exist where some of the molecules will stick to the surface and others still bounce back. However, if the surface is replaced by an orifice, where all the molecules passing through will not return, this could be exactly the case with the 18-fin cylinder. If the orifice is then bounded by deep fins on a surface at a low enough temperature to freeze out the gas, the gas molecules undergo multiple collisions with the cold surface and most are condensed. Once the depth of the fins is sufficient to freeze out all the molecules, further increase in the depth will have no effect on the cryopumping rate. With this in mind, it is obvious that the total surface area cannot be used to calculate meaningful pumping speed per unit area. One must instead use the envelope area. When this new surface area is used, the capture coefficient of the envelope is found to be unity, that is, every molecule that passes through the hypothetical envelope area is condensed.

The use of fins or honeycomb structure on a cryosurface to increase capture probability in cryopumping will be important in the design of cryopanels. However, there appear to be two limitations. First, there is an optimum length for the fins, which is a function of the thermal conductivity of fin material and of the ratio of the separation of the fins to their depth. The second apparent limitation is the amount of non-condensable gases present in the system. In these tests, the purified

CO_2 gas contained approximately 20 parts noncondensables for every 10^6 parts CO_2. It was observed that the frost deposit covered all of the fins down to the cylinder, and there was no visible deposit on the cylinder itself between the fins; the results indicated a capture coefficient of one. Another test (Ref. 4) was performed under the same conditions with the exception that the CO_2 contained approximately 400 parts noncondensables for every 10^6 parts CO_2. In this case, it was observed that the visible CO_2 deposit appeared only on the tips of the fins, and the capture coefficient was calculated to be approximately 0.35. This is presumably caused by the concentration of the noncondensables in the space between the fins. The noncondensables would be prevented from escaping by the inflowing CO_2 gas, and would in turn prevent the CO_2 from reaching the bottom of the space between the fins, thus reducing the effective depth of the fins. Although there is some disagreement between this picture of the effect of noncondensables and the simple kinetic theory predictions, there is no lack of evidence for the reality of the effect itself.

4.3 PARALLEL PLATE CRYOSURFACES

Two sets of tests were performed with the parallel plate cryosurfaces: the first with the plates at one-inch separation, and the second with the plates together. The results of both tests are shown in Fig. 6. Again, the transition range between the free-molecular flow and continuum flow regimes is clearly defined for both cases in the form of an S-shaped curve. Examining the part of the curve in the lower pressure range where free-molecule conditions prevail, it can be seen that the pumping rate is approaching a constant value, approximately 2400 liters/sec for the plates separated one inch. Using a capture coefficient of one for the open area between the plates and a capture coefficient of 0.55 for the external surfaces, which is the capture coefficient obtained from the experimental data with the plates together, a theoretical pumping rate can be calculated. This theoretical pumping rate is 2465 liters/sec which is approximately equal to the experimental value obtained in the test.

This result agrees with the results obtained from the 18-fin cylinder, i.e., in both cases the open area of the cryosurface appears to have a capture coefficient of one for a very pure condensable gas in the free-molecular flow region.

4.4 TRANSITIONAL FLOW PHENOMENA

It is significant that pumping rate increases in the region above the free-molecular flow region in the cryopumping of CO_2 at liquid nitrogen temperature. The unpublished data at other laboratories did indicate on occasion that experimental cryopumping rate exceeds that based on kinetic theory $A(RT/2\pi M)^{1/2}$. Some explain this discrepancy as inaccurate experimental data, others as a directed flow effect caused by one-directional motion of molecules to the cryopanels. However, the data may be actually correct if they happen to be for the transition or continuum regions.

This increase in pumping rate eventually tapers off at higher pressures where continuum flow phenomena usually occur. It has been found experimentally that the pumping rate in the continuum flow regime will somewhat obey orifice flow theory prediction, $A(\gamma RT/M)^{1/2}$. These continuum flow phenomena in cryopumping could possibly be related to orifice flow theory, considering the case where gas molecules at the chamber pressure are flowing through an imaginary orifice or conductance restriction. Since the pressure at the cryosurface is very small in comparison to that of the system, a flow process involving adiabatic expansion towards the surface could also be realized.

If $A(\gamma RT/M)^{1/2}$ and $A(RT/2\pi M)^{1/2}$ are chosen as the two limiting pumping rates, then the transition region is defined. An interesting correlation can be obtained by plotting pumping rate in the transition region, on normal probability paper, versus the logarithm of pressure. The pumping rate is plotted as the percentage transition which is defined as:

$$\% \text{ transition} = \frac{(P.R.)_t - (P.R.)_{fm}}{(P.R.)_c - (P.R.)_{fm}} \times 100$$

Figure 7 shows the probability plot for the 3-fin cylinders, and Figure 8 shows the plot for the 18-fin cylinder and the parallel plate cryosurfaces. Although there is considerable scatter in the data, all the plots show an approximately linear relationship.

The reasons for this linear relationship are not known at present. However, it seems reasonable to assume that the pressure for 50 percent transition may be used to calculate a mean free path which should be comparable to the dimensions of the cryosurface. The symmetry of the transition region, implicit in the linear relationships shown, is intriguing. It indicates that, at least for cryopumping, the transition region is subject to quite definite rules and should be subject to theoretical analysis when sufficient data become available.

The following table gives a comparison of the cryosurface dimensions and the dimensions determined from the 50-percent transition point:

Cryosurface	Cylinder Length, in.	Cylinder Diameter, in.	Fin Depth or Plate Separation, in.	$(P.R.)_{fm}$, liters/sec	$(P.R.)_c$, liters/sec
3-Fin Cylinder	3.5	0.75	0	600	1150
3-Fin Cylinder	3.5	0.75	0.5	950	1800
3-Fin Cylinder	3.5	0.75	1.0	1540	2490 (est.)
18-Fin Cylinder	3.5	1.00	0.5	1850	5500 (est.)
2 Parallel Cylinders	1.0	4.00	0	1790	5300
2 Parallel Cylinders	1.0	4.00	1.0	2400	7200

Cryosurface	λ at 50% Transition, in.	$(P.R.)_c/(P.R.)_{fm}$	$\left(\frac{\gamma RT}{M}\right)^{1/2} \Big/ \left(\frac{RT}{2\pi M}\right)^{1/2}$
3-Fin Cylinder	0.66	1.92	2.97
3-Fin Cylinder	1.04	1.90	↕
3-Fin Cylinder	1.34	1.91	↕
18-Fin Cylinder	0.67	2.97	↕
2 Parallel Cylinders	5.05	2.96	↕
2 Parallel Cylinders	1.85	3.00	2.97

From the table it is quite obvious that although the ratio, $\sqrt{2\pi\gamma}$, is valid for estimating the increase in pumping speed for certain configurations (i.e., parallel plates), it is not valid for all configurations. Therefore, it will be necessary to study many other configurations before a generally valid relationship can be developed.

5.0 CONCLUSIONS

The study of cryopumping in the higher pressure ranges has shown a definite effect of flow regime on the pumping rate of a cryosurface. From the results obtained in the gas kinetic regime and the transition range, the following conclusions are made:

1. The addition of fins to a cryosurface can increase the pumping rate and lead to capture coefficients of nearly unity.
2. The advantage of fins is greater for pure condensable gases than for those contaminated with noncondensables.
3. The pumping rate of a cryosurface is greater in the continuum range than in the free-molecular range by factors ranging up to nearly three-fold.
4. At pressures between the continuum and free-molecular regions there is a smooth transition in the pumping rate.
5. The change of pumping rate with log-pressure in the transition range follows a Gaussian distribution.

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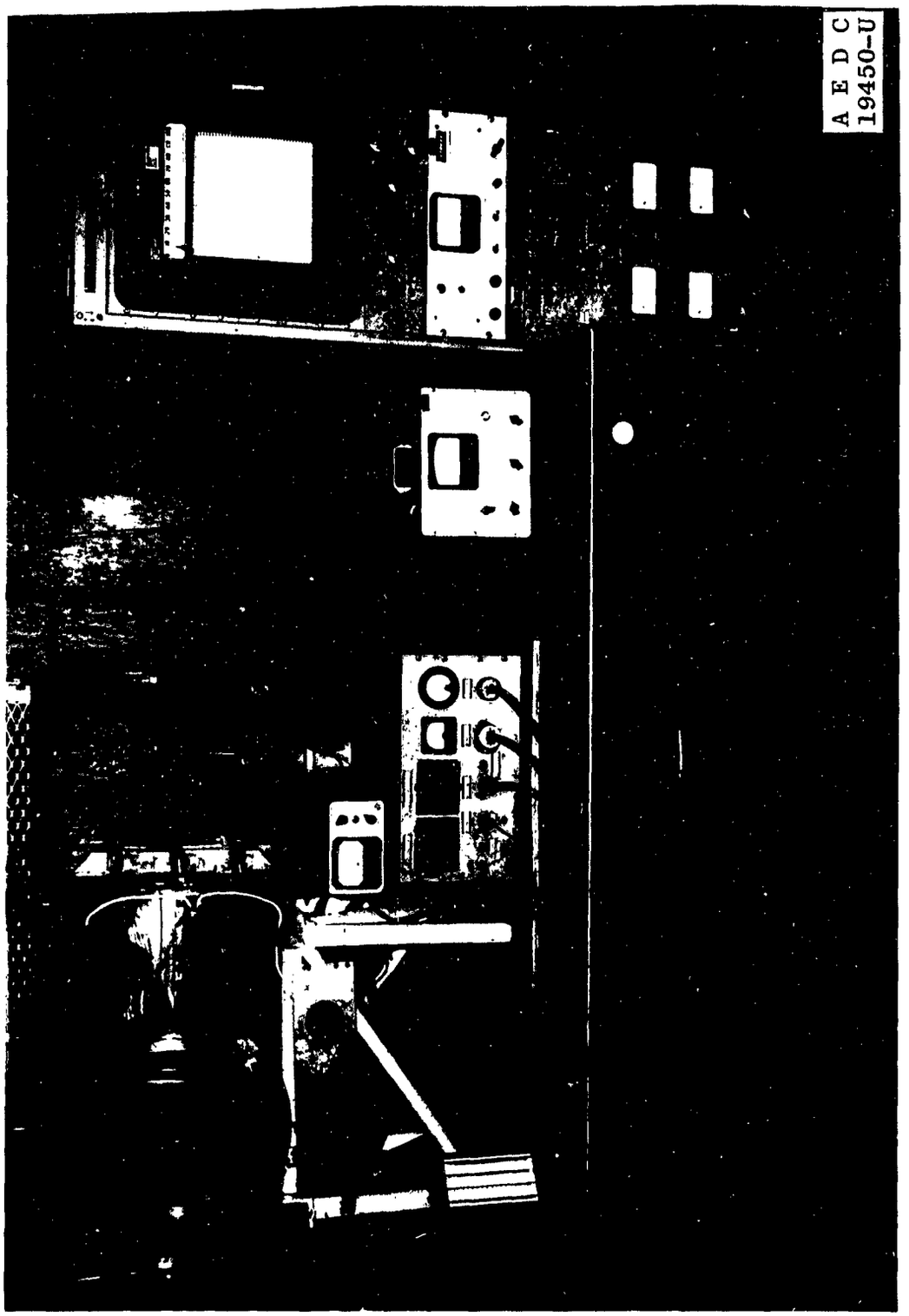

Fig. 1 Test Equipment

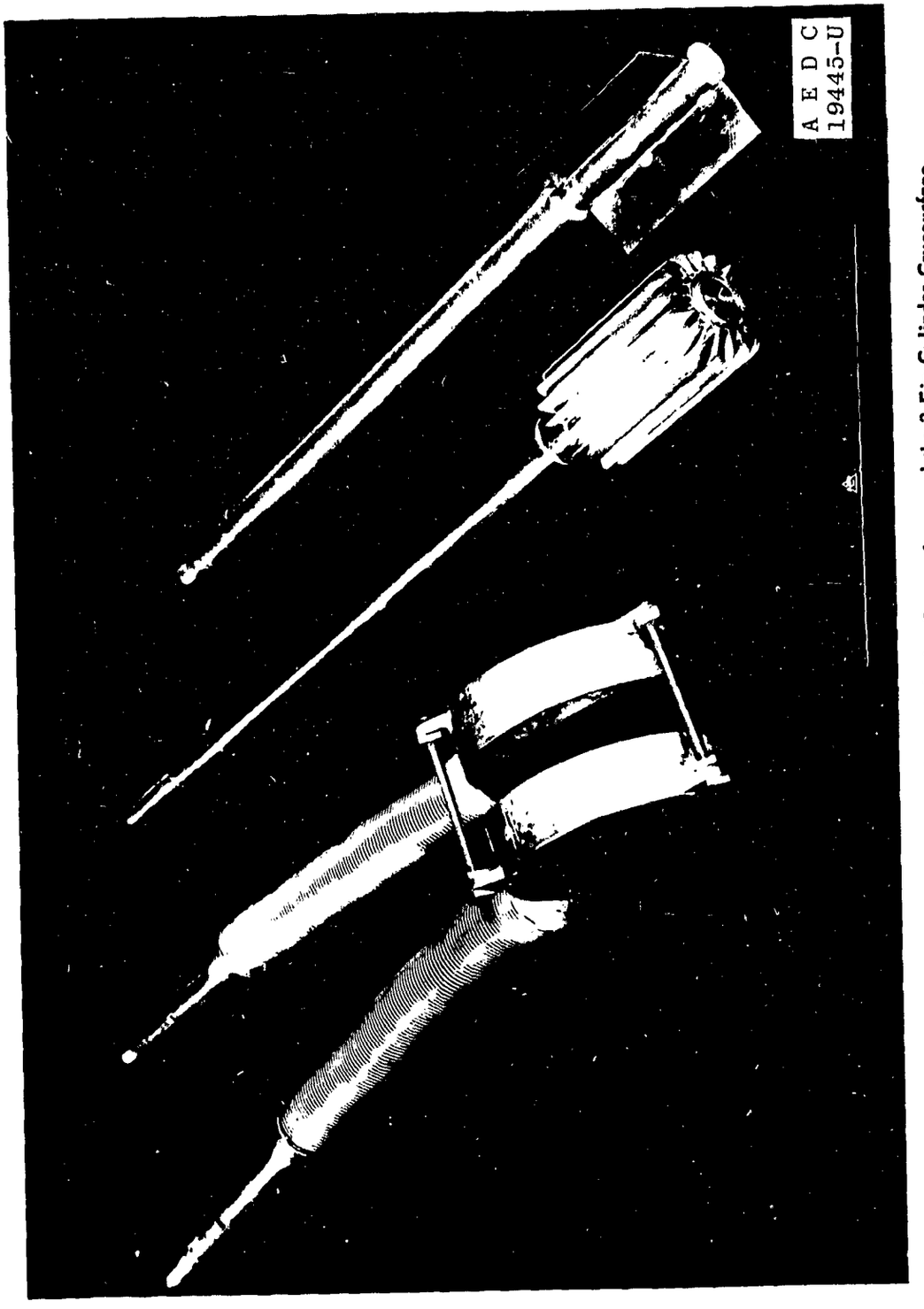

Fig. 2 Parallel Plate Cryosurface, 18-Fin Cylinder Cryosurface, and the 3-Fin Cylinder Cryosurface

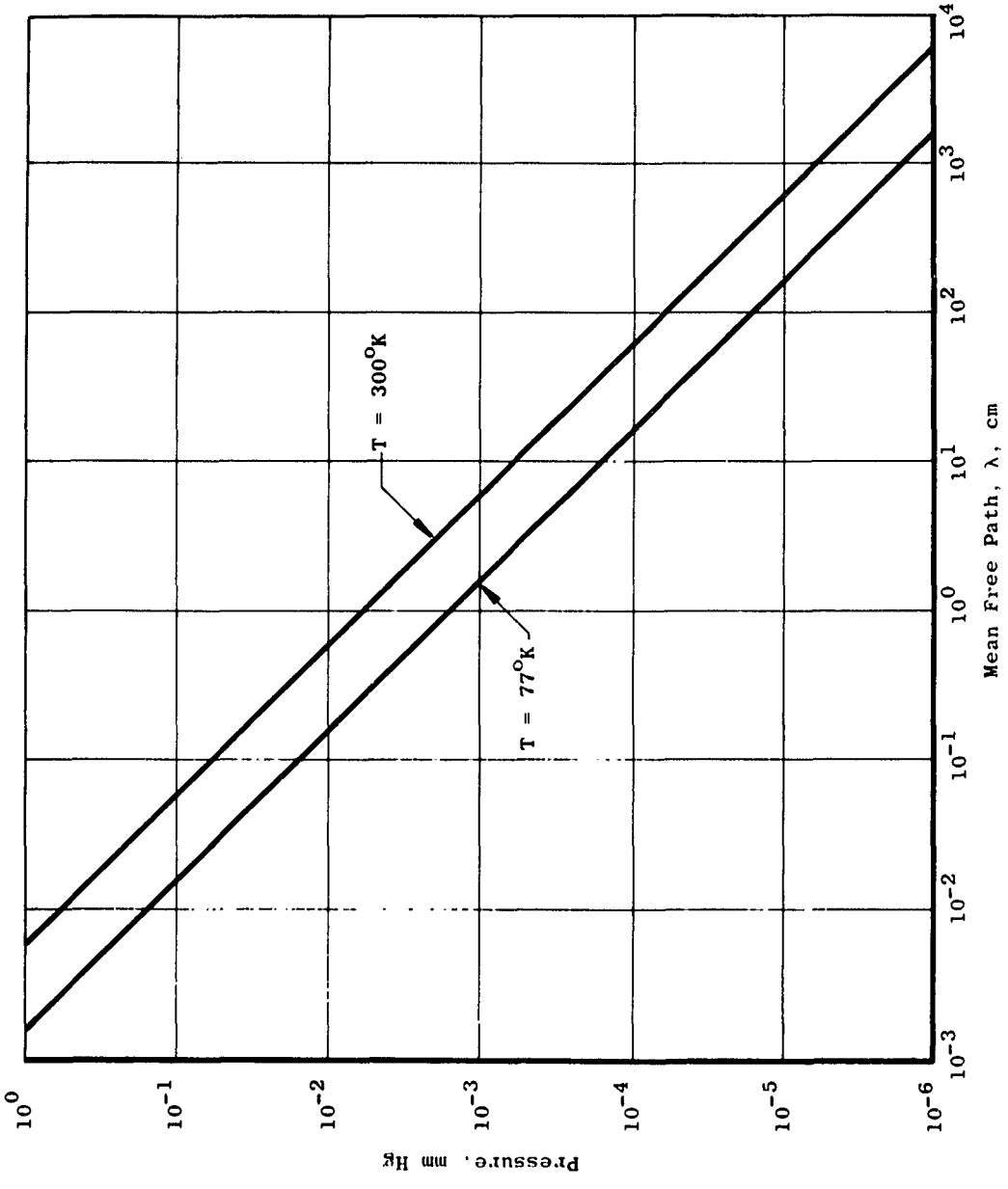

Fig. 3 Mean Free Path for CO_2 vs Pressure and Temperature

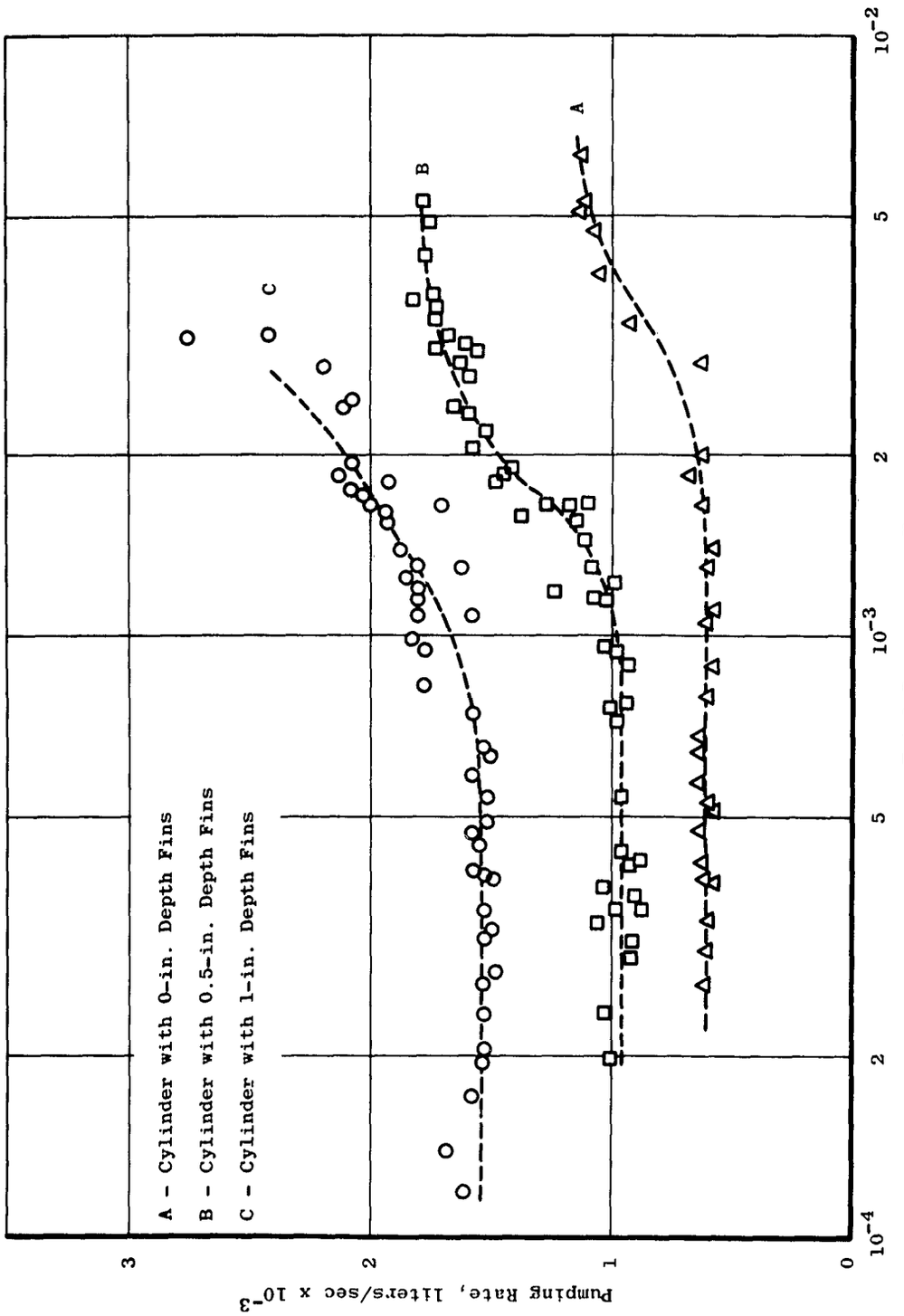

Fig. 4 Pumping Rate vs Pressure for 3-Fin Cylinder Cryosurface

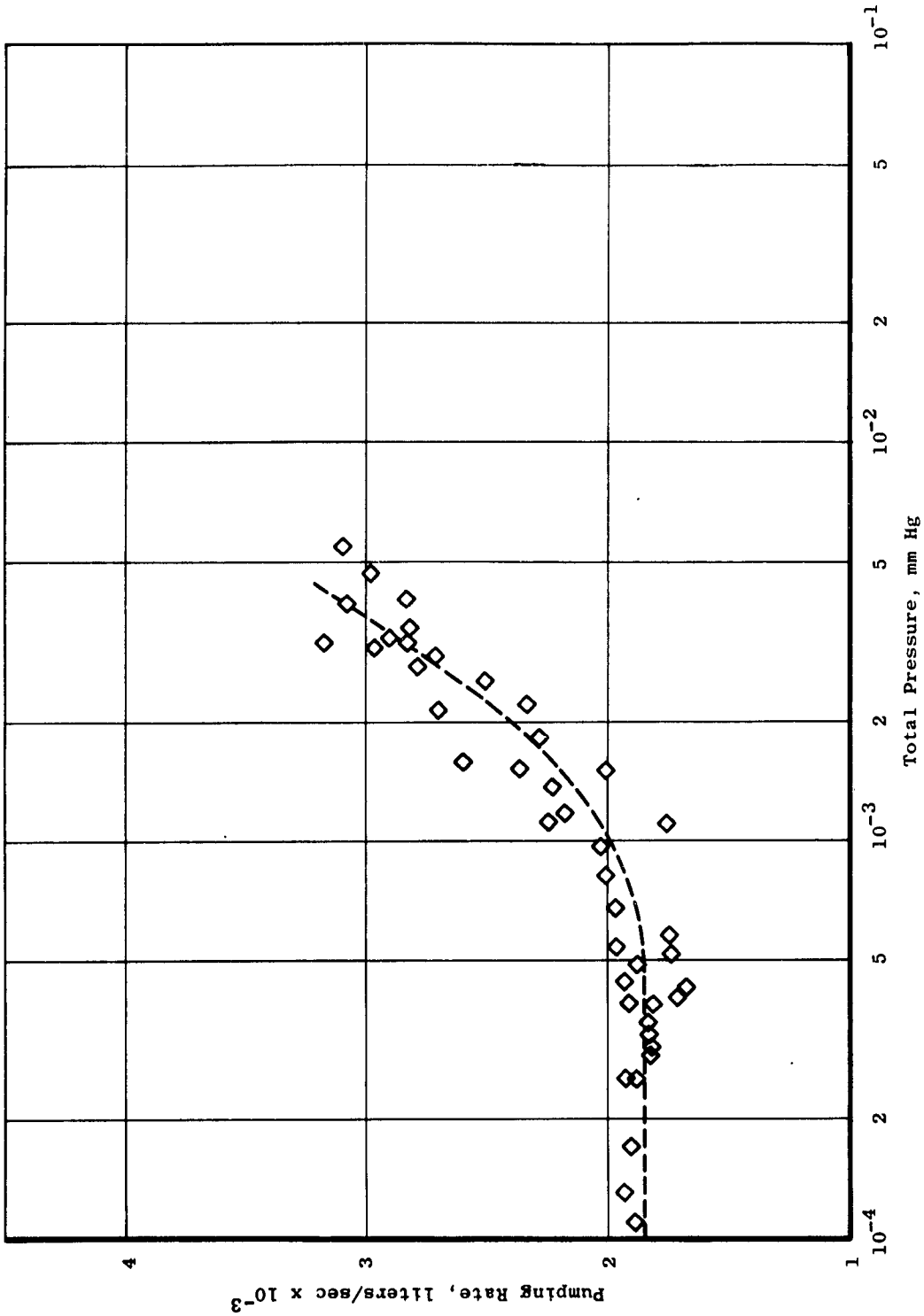

Fig. 5 Pumping Rate vs Pressure for 18-Fin Cylinder Cryosurface

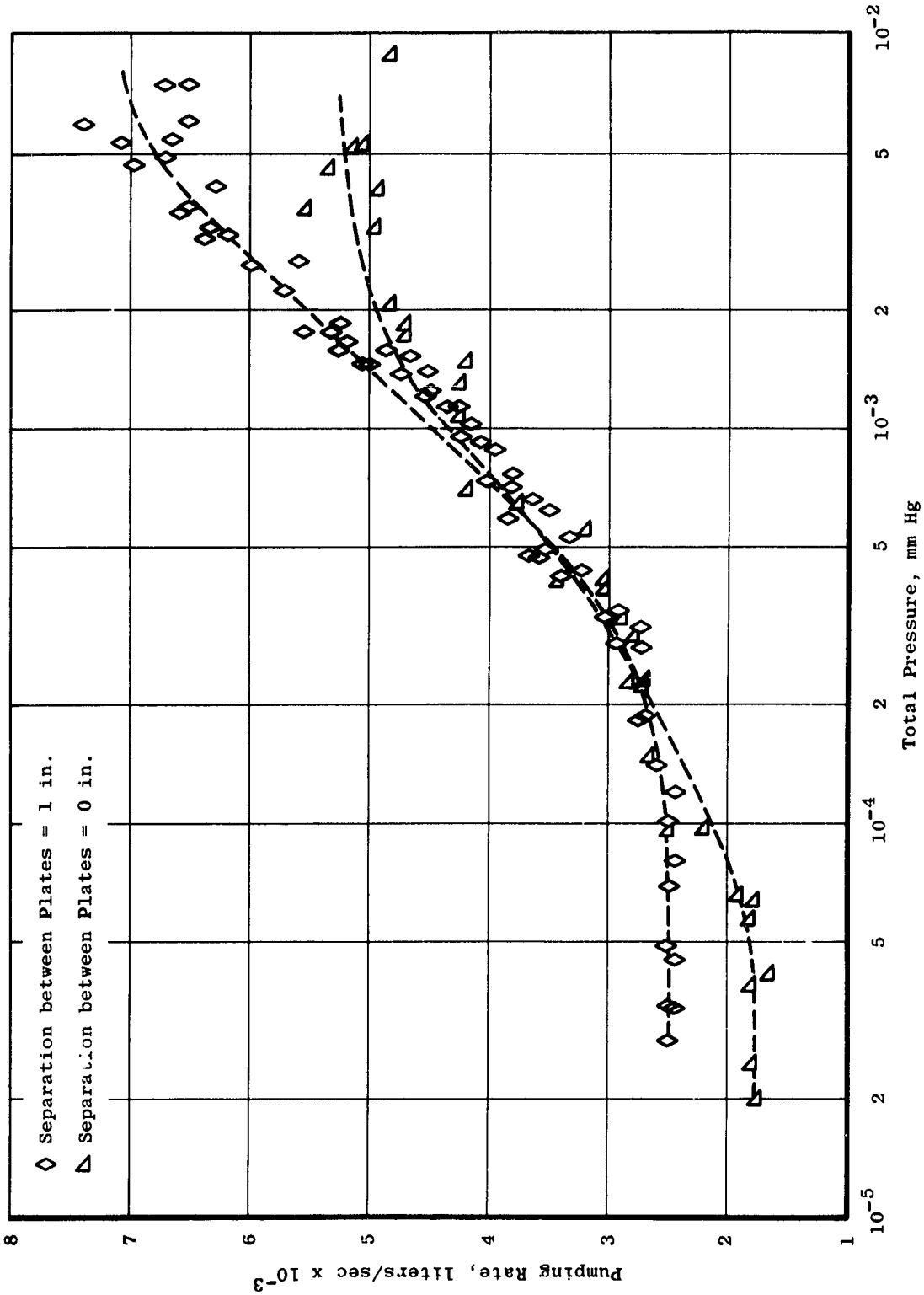

Fig. 6 Pumping Rate vs Pressure for Parallel Plate Cryosurfaces

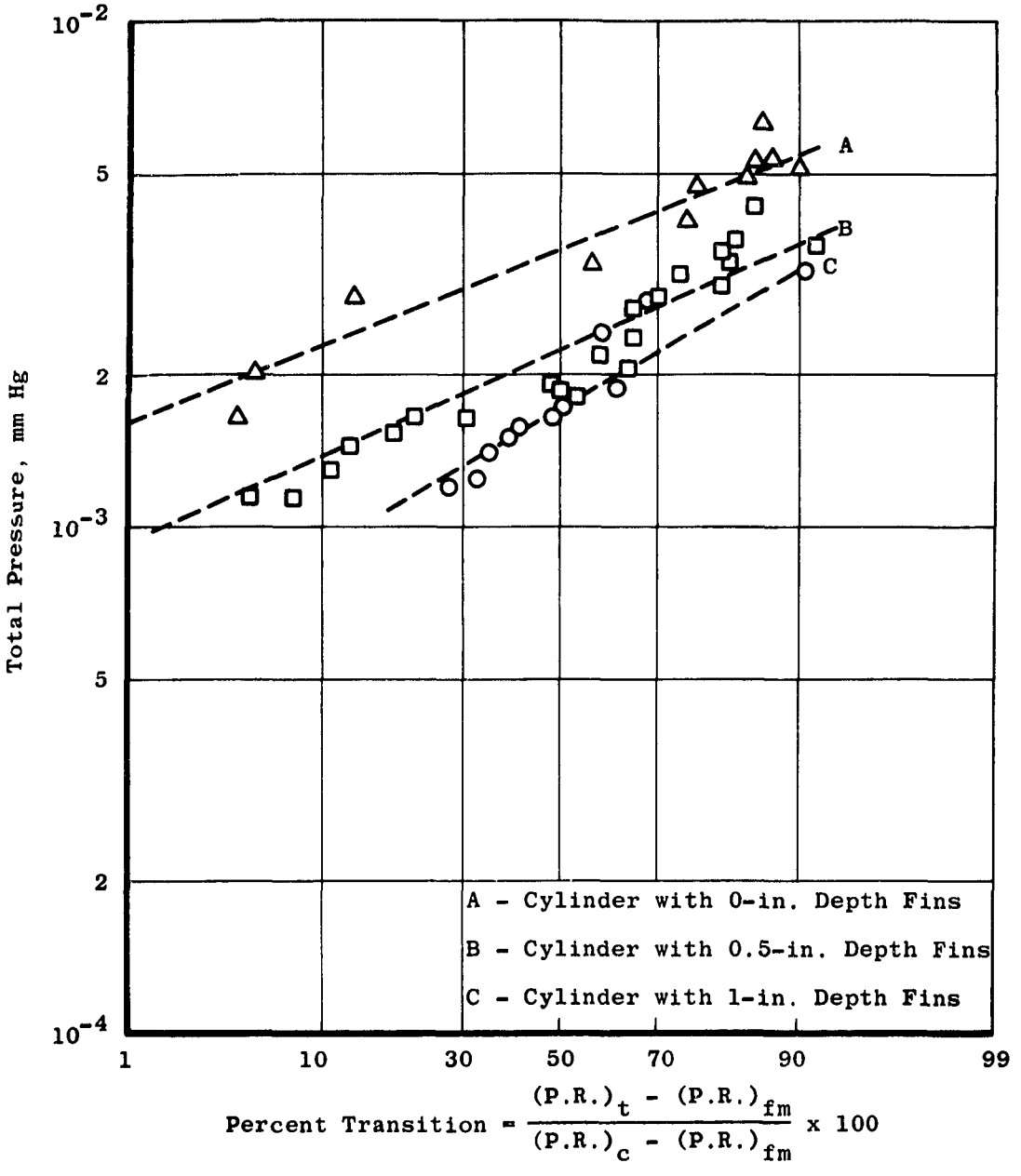

Fig. 7 Log-Probability Plot of Transition Range for 3-Fin Cylinder Cryosurface

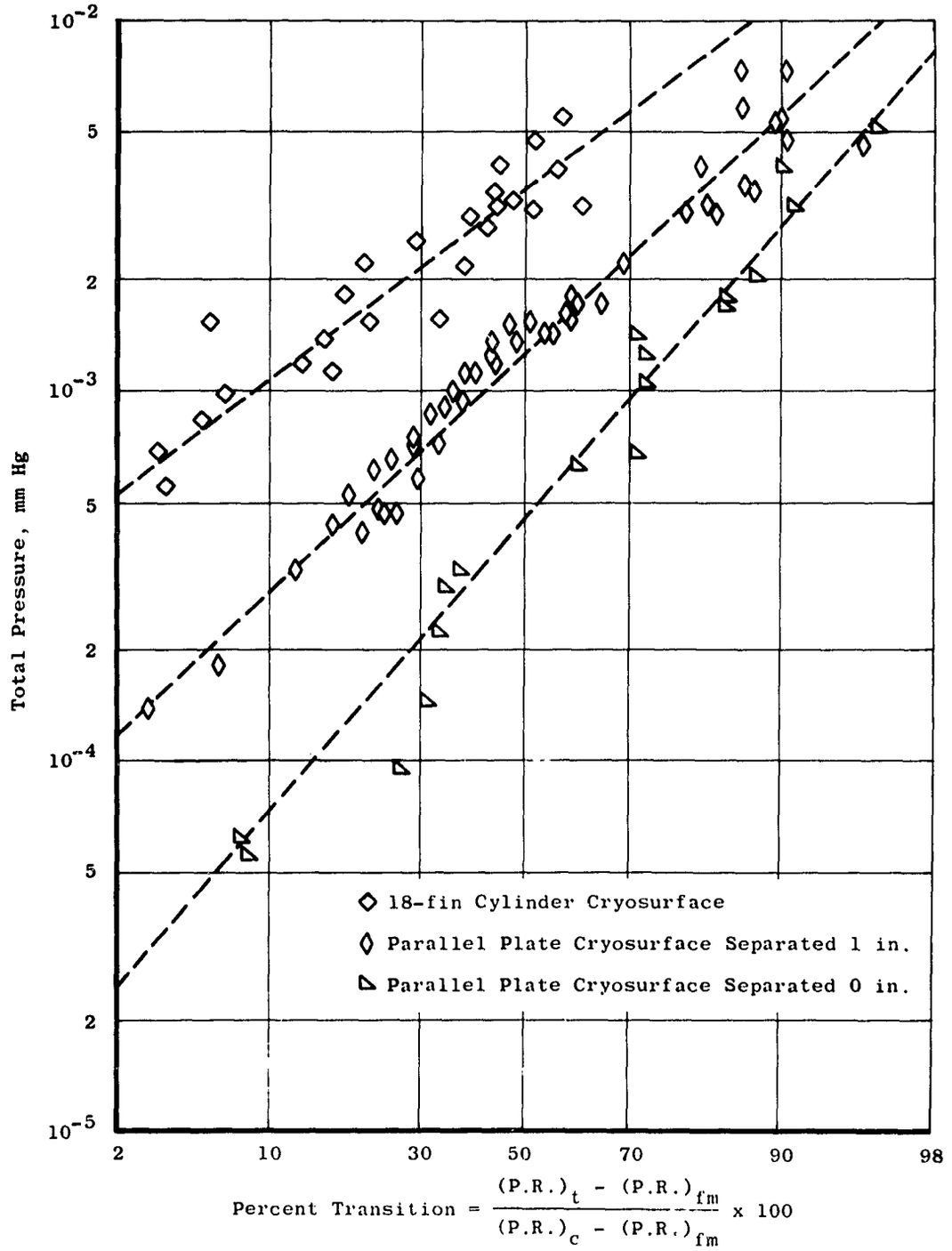

Fig. 8 Log-Probability Plot of Transition Range for the Parallel Plate and the 18-Fin Cylinder Cryosurfaces

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Rpt. No. AEDC-TDR-62-46. INITIAL STUDY OF THE EFFECT OF CRYOSURFACE GEOMETRY ON CRYOPUMPING. April 1962, 22 p. incl 7 refs., illus., tables.
Unclassified Report

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2. Surfaces
3. Pumps
4. Vacuum systems
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II. Contract AF 40(600)-800 S/A 24(61-73)
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